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Santa Monica, California 90406

# APPLICATION OF ELECTRON BEAMS IN SPACE FOR ENERGY STORAGE AND OPTICAL BEAM GENERATION

Robert M. Salter

## SUMMARY

Examination is made of the potential for in-space-propagated electron beams for storage rings that buffer solar energy collected in low-orbit-altitude satellites. An example case in a 3000-mile equatorial orbit utilizes a nine-beam helical configuration to store 5.8 TJ in 60 MeV electrons. Electron energized optical and rf generators are covered including transmission of a 3 GW synchrotron radiation beam of  $\lambda_c = 1000\text{\AA}$  over 6000 km to a ground receiver with an 827 m aperture.

## INTRODUCTION

Systems described here are of interest for NASA programs for in-space collection and transmission of energy. Customarily such system concepts have centered on geosynchronous satellites. Here we consider satellite systems at lower orbit altitudes ( $\sim 3000$  miles) but still in the equatorial plane.

At the lower orbit altitudes we lose perhaps a factor of two in solar energy due to earth shadowing but profit by a five times or more increase in payload capability. Also, ground receivers for equal transmission gain (solid angle) need employ only three percent as large a collection area. On the other hand, the 3000-mile-high satellites circle the globe every  $3\frac{1}{4}$  hours and thus do not remain constantly in view as do the geosynchronous ones.

Systems must be devised to store energy for 156 minutes and transmit it to ground stations in 39 minutes. If we assume gigawatt-level solar collection and storage, then space-to-ground transmission must be at the several gigawatt level.

The systems examined here utilize electrons in an unexplored space propagation mode needed to permit large storage rings in space. This same propagation phenomenon might also be useful for electron-beam space-to-space power transfer for specialized situations. Storing 0.62 gigawatts for 156 minutes produces 5.8 Terrajoules.

For this hypothetical model we assume collection stations near San Diego, California and Miami, Florida (with perhaps an alternate at Brownsville, Texas). With a (nominal) 3750-mile range from a 3000-mile-high equatorial satellite, only high elevation angles can be assumed. A total in-view coverage of  $72^\circ$  or one-fifth of a satellite's orbit period is estimated with the San Diego station carrying only 40% of the load.

## ELECTRON ENERGY STORAGE RINGS

Electron storage rings potentially can be used for storage of large amounts of energy. A relativistic electron beam is an extremely lightweight medium for this purpose. Even with associated beam-handling and generating hardware, overall system weights portend to be low enough for space applications consideration.

Maximum permissible power levels in an electron beam increase as  $\sim E^2$  (where E is the electron particle energy). This functional dependence is due to Alfvén current limitations of  $i_{\max} = 17,000 \beta \gamma$  where  $\beta$  is essentially unity and  $\gamma$  is roughly  $2 \times E(\text{MeV})$  for values of  $E > \text{several MeV}$ . Thus, maximum beam power ( $P_{\max}$ )  $\sim 3.4 E^2$  GW.

$$\text{For } E = 5 \text{ MeV} \quad P_{\max} = 85 \text{ GW}$$

$$\text{For } E = 60 \text{ MeV} \quad P_{\max} = 1.2 \times 10^{13} \text{ Watts}$$

$$\text{For } E = 1 \text{ GeV} \quad P_{\max} = 3.4 \times 10^{15} \text{ Watts.}$$

A storage ring employing, say, 60 MeV electrons will need a perimeter of 0.48 seconds (or 89,000 miles) to contain the  $5.8 \times 10^{12}$  Joules assumed for one example. Quite obviously this places special concern on ring configuration and also suggests higher electron particle energies to reduce ring path length.

Typical electron trajectories in the Earth's magnetic field in the equatorial plane are shown in Figure 1. Figure 1a shows electrons injected horizontally at 1000 (statute) miles altitude. Due to decreasing field radially outward the ring trajectory does not return to its starting point. This gradient effect is also seen in Fig. 1b where electrons injected at an angle to the equatorial plane form a skewed helix. With very high energy for electrons we find trajectories as shown in Figures 1c and 1d.

An electron beam might be expected to diverge rapidly due to repulsion of its like-charged particles. However, in a highly relativistic beam, this repulsive (coulomb) force is very nearly offset by the electron beam's radially inward self-field arising from its current of charged particles. The difference between these two forces is proportional to  $1/\gamma^2$  (where  $\gamma$  is a measure of the relativistic energy in rest mass units). Thus for example at  $E = 5 \text{ MeV}$ ,  $\gamma \sim 10$  and the force difference is 1 percent.

If one percent of the electron charge is neutralized by, say, the presence of positive ions then the repulsive and self-field forces will be in equilibrium and the beam will not diverge.

In Earth's space above 300 km there are enough ambient ions to cause the above so-called space-charge focusing. The postulated mechanism is illustrated in Figure 2. High-energy beam particles "kick" the low-energy ambient electrons out of the beam path. The more massive, slower moving space ions are essentially stationary. The electron beam will expand (or contract) to encompass just the right number of ions to maintain an equilibrium beam envelope.

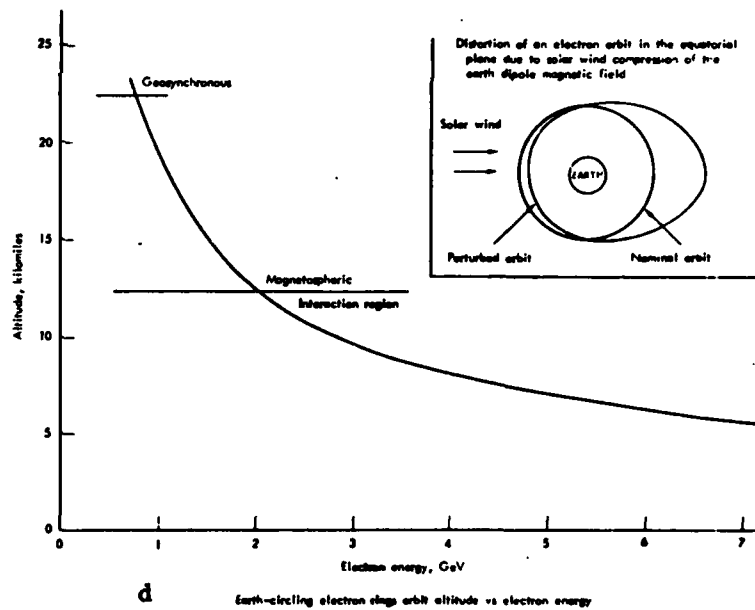
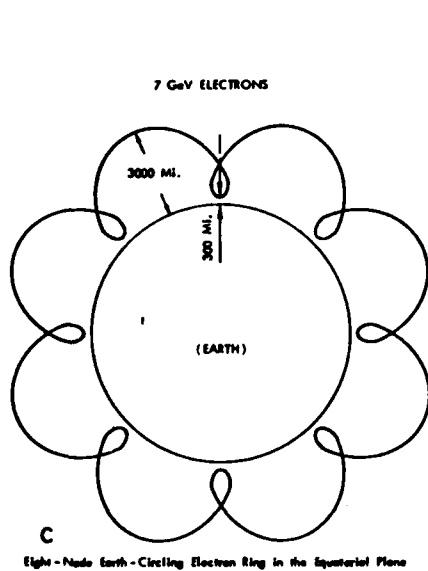
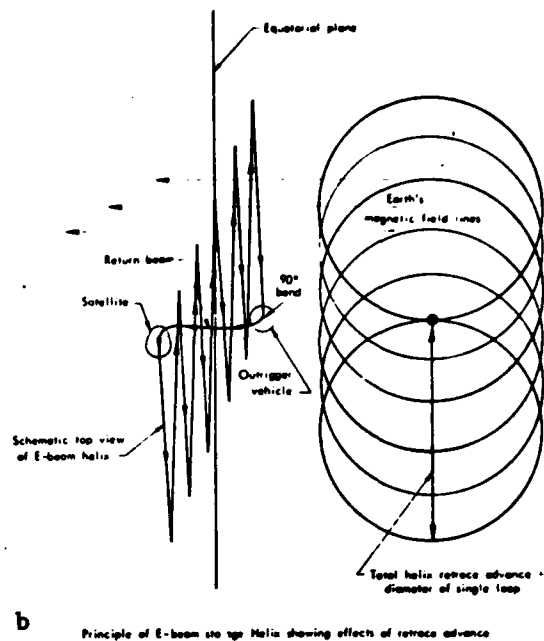
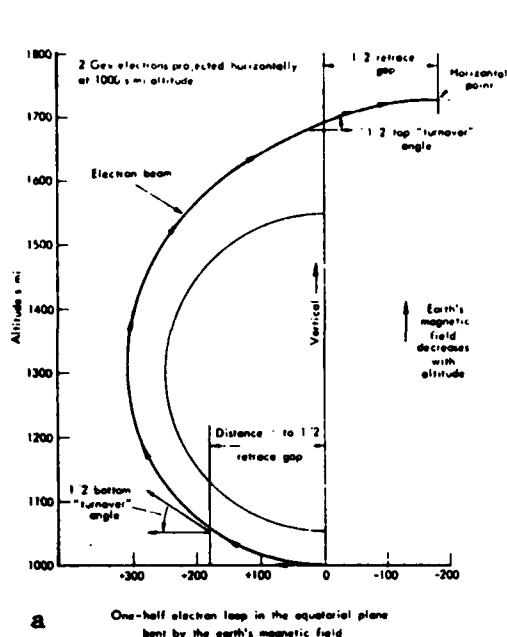


Fig. 1—Electron trajectories in space

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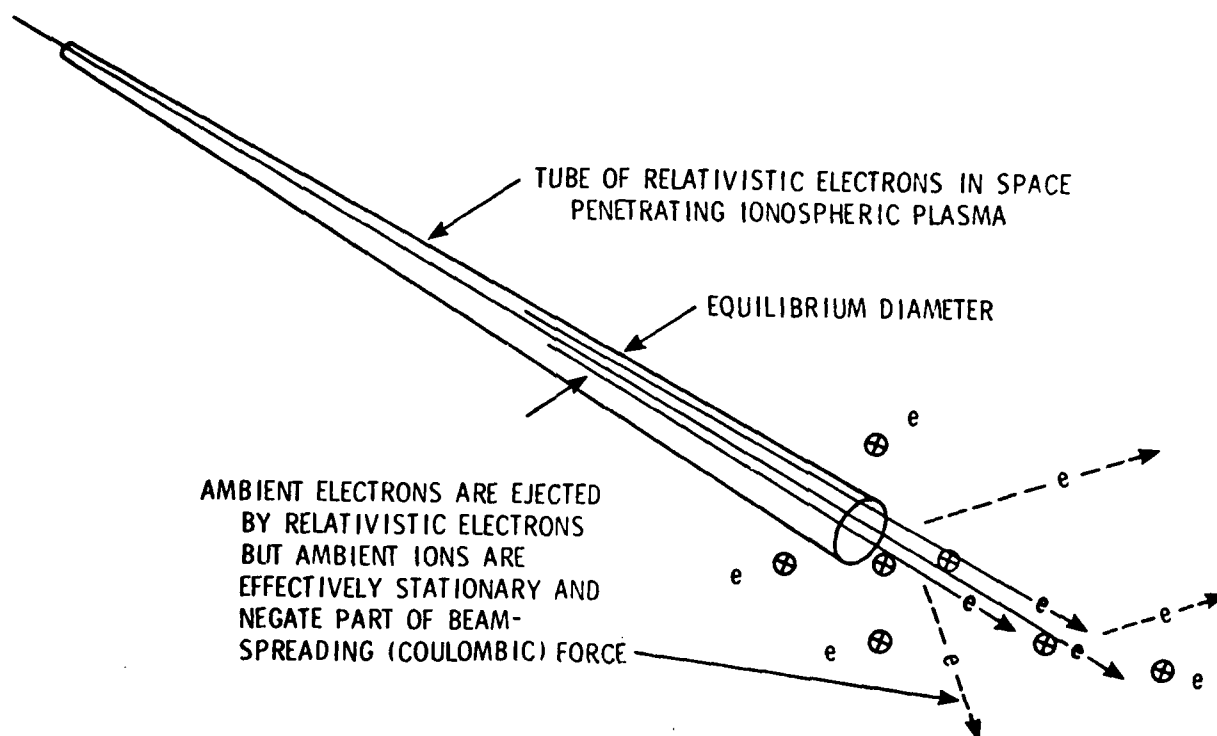


Fig. 2—Schematic illustration of e-beam propagation in the ionosphere through partial neutralization of the electron charge separation force

This phenomenon has been demonstrated in laboratory experiments, but the propagation of space-charge focused beams over large distances in space is untested. Calculations show that above several hundred miles dispersive effects through multiple scattering will be small.

It is apparent that if such focusing can be achieved, electron beams can maintain small cross sections for thousands of miles. Figure 3 compares electron propagation to laser and neutral beam radiation.

With the level of ion density anticipated from 300 km out to several thousand miles ( $\sim 10^4$  ions/cc), with electron particle energies of 50-500 MeV, and with beam currents of kiloamperes we can expect equilibrium beam diameters of a meter or less. Increased ion population in the satellite region will reduce beam diameter permitting multi-kiloampere-current beams at manageable sizes.

Assuming that space-charge focusing is a feasible mechanism (with perhaps more conventional magnetic focusing techniques used in satellite beam handling equipment) we can consider an electron storage system as shown in Figure 4. On-board sensors and servo-mechanism-controlled magnets perform beam handling and provide for continual correction in direction.

Nine interleaved helices of 62 loops each will provide (at 3000 miles altitude, equatorial plane) the needed .48 sec storage ring perimeter. Each loop is 51 miles in diameter. The interleaved arrangement is needed because of the gradient-effect advance shown in Figure 1b. A separation of one mile between mother satellite and outrigger provides  $\sim 10$  ft spacing between circulating beams. (In the solar collection satellite considered here the entire system may be mounted on a mile-long solar array structure which also provides a base for a power-transmitting optical beam system to be described later.)

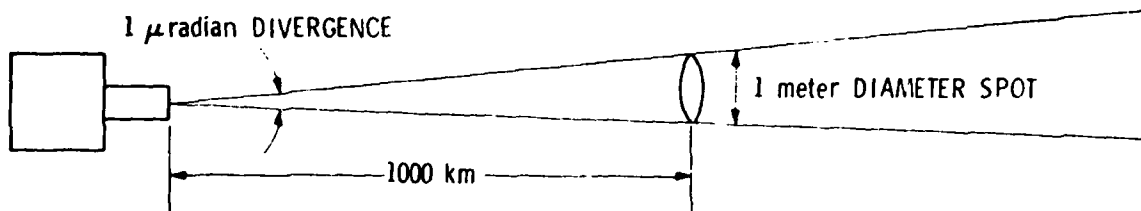
#### ENERGY CONVERSION

Initial generation of electrons by solar-array-produced power can be performed by various particle accelerator types depending on current and particle energy levels desired. For our 60 MeV example initial production of a large current of 10 MeV electrons could be accomplished by a pulse diode with the remaining acceleration via an induction linac "reflexotron" scheme<sup>(1)</sup> or shuttle microtron.<sup>(2)</sup> The durability of the pulse diode might be of concern in which case a more conventional source of one or more electron guns followed by Cockroft-Walton accelerating elements could be employed.

Customary accelerator beam-switching magnets, and injection and extraction systems can be considered.

The problem of conversion of the high-energy storage ring electrons can be solved in various ways. Deceleration to produce a lower-voltage electrical current can be accomplished by reversing the acceleration process in a cyclic accelerator of the type described above. Alternatively we could





LASER OR NEUTRAL BEAM ( $H^0$ ) PROPAGATION



CONSTANT SMALL DIAMETER BEAM (SEVERAL cm)  
FOR THOUSANDS OF MILES

ELECTRON BEAM PROPAGATION (IN IONIZED SPACE REGIONS)

Fig. 3—Schematic comparison of propagation of radiation beams in space  
(vertical scale exaggerated  $10^5\times$ )

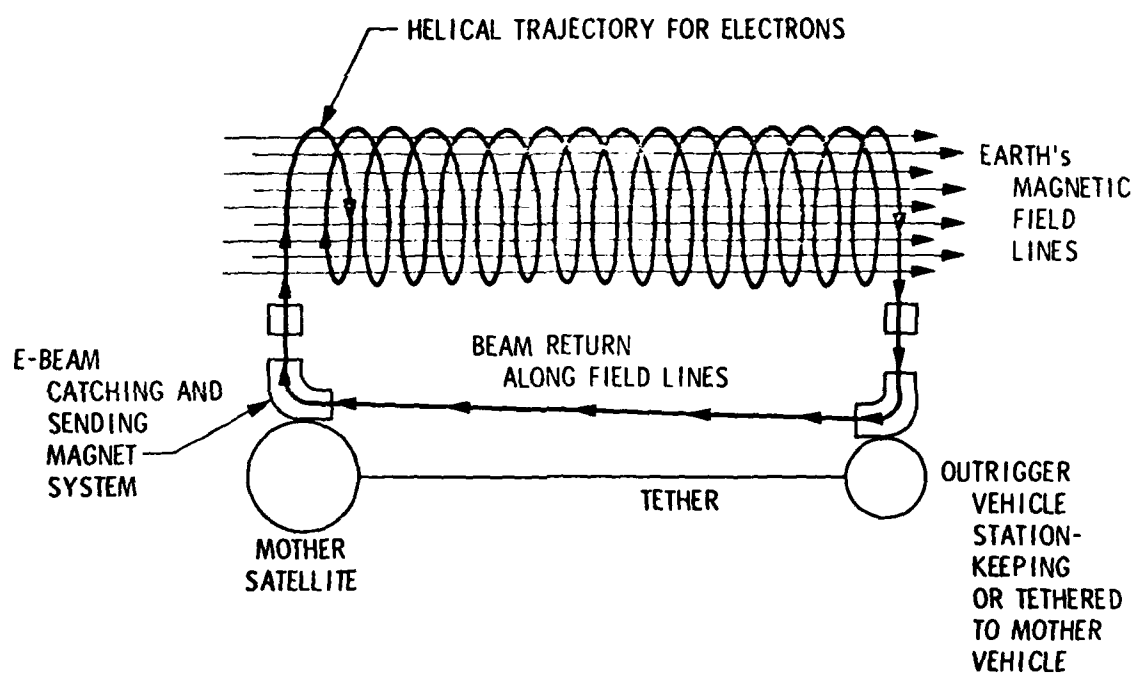


Fig. 4—E-beam helical storage loops in space

simply convert the electron energy to heat, say, a 2000°K MHD closed-cycle engine.

Yet further we can use electrons directly. By placing a "C" magnet such that its field lines are transverse to electron beam paths in a lasing medium we can trap virtually all of the electron energy in this way. Such would be useful for pumping, say, a CO<sub>2</sub> IR laser.

Figure 5a shows a similar magnet but this time with a vacuum rather than a lasing medium in the field. The trapped electrons will now lose energy through synchrotron radiation which in turn can be employed to pump a laser(s) in the visible light region. Figures 5b to 5d depict other schemes which rely on "shower" plates to reduce electron energy through production of  $\gamma$ -rays and secondary electrons (such as in a spark chamber).

More elegant methods for utilizing electrons include a laser beam amplifier as seen in Figure 6. This scheme is the optical counterpart to a klystron for amplifying rf signals. A device under study by ORNL utilizes 150 MeV electrons--in the regime of interest for storage rings.<sup>(3)</sup>

Another erudite approach is found in the free electron laser.<sup>(4)</sup> Here by proper coherent interaction with travelling electromagnetic waves, electron bremsstrahlung is emitted in the monochromatic, coherent form characteristic of a laser beam.

Both of these above schemes will need an electron ring--not necessarily for energy storage--but to conserve electrons in the acceleration process. Electrons will give up only a small part of their energy per pass and must be continuously circulated through the lasing device for efficient operation. The energy distribution of the electrons also is modified on each pass so that a set of make-up coils is needed to continuously "refresh" the electrons. In essence this process then is one of transforming rf electromagnetic (EM) radiation energy into laser EM radiation with the ring electrons serving as a working fluid.

The electron storage ring for this purpose can be quite small and serviced by a conventional accelerator--or it can be the same large ring that is used for energy storage. (Figure 7 shows an alternate form of space storage ring.)

It should be noted that the free electron laser selects only highly special modes out of all those assigned to the circulating ring electrons. For this reason it is not capable of high power even with very high beam current. The author has calculated that only kilowatt level laser beams could be derived at electron ring currents approaching Alfvén limiting values.

Other schemes than optical can be employed to extract and transmit energy from the electron beams (e-beams). A form of auto-accelerator (or auto-resonator) can produce copious amounts of rf radiation from an e-beam.<sup>(5)</sup>

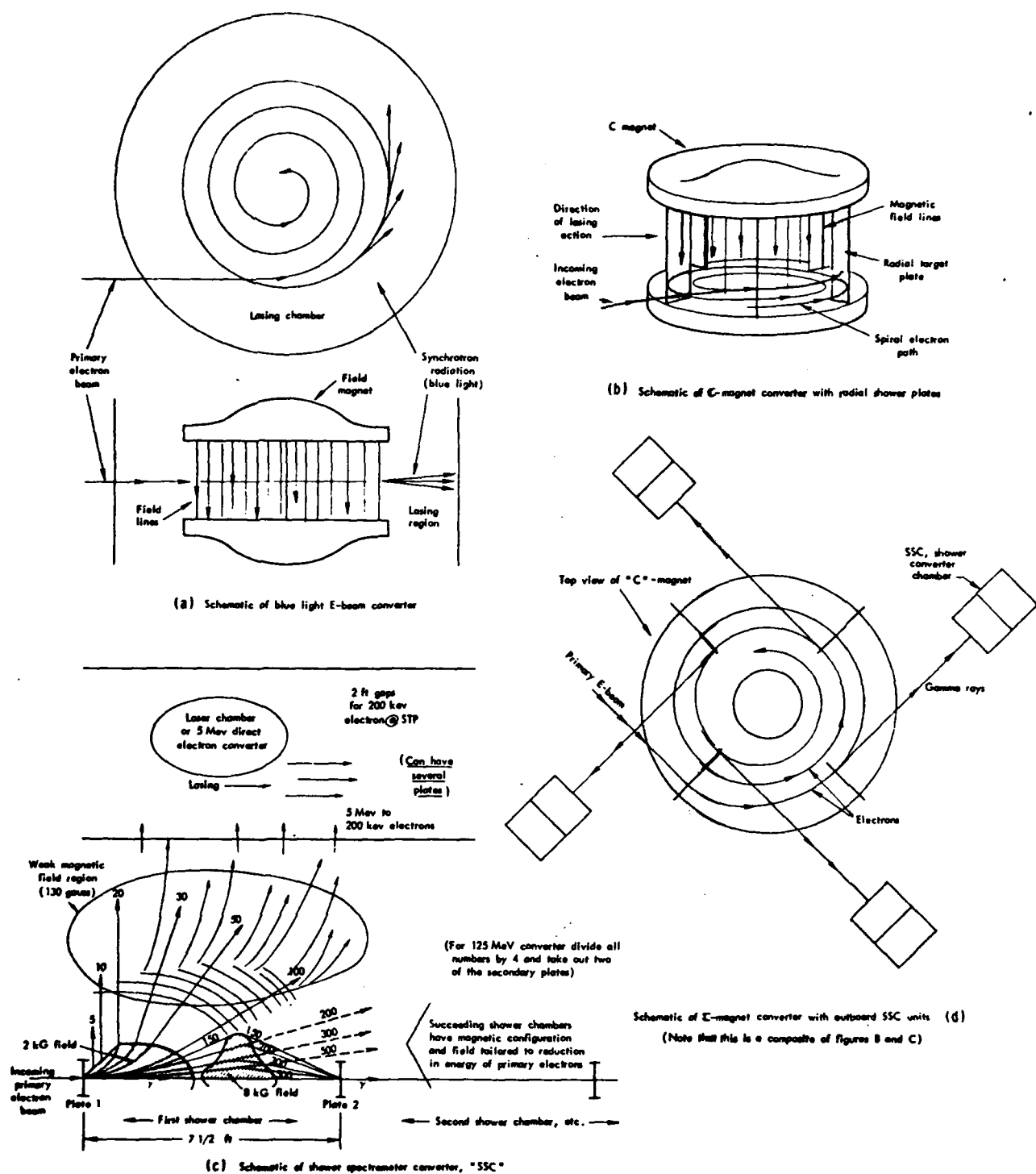


Fig. 5—Electron energy conversion schemes

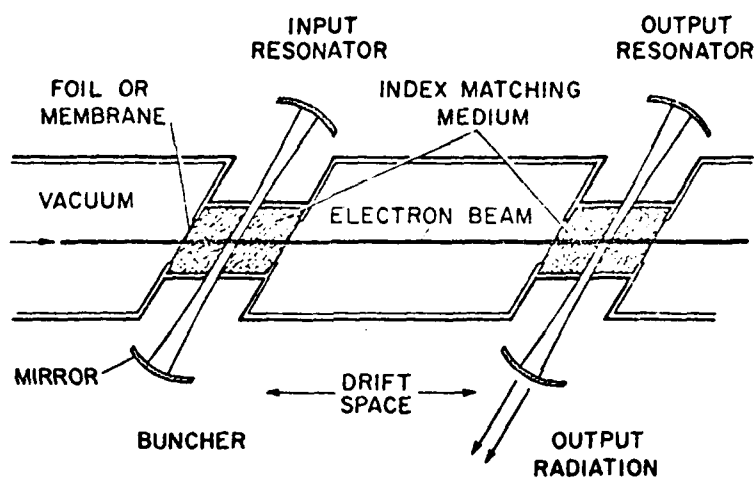


Fig. 6—Optical klystron

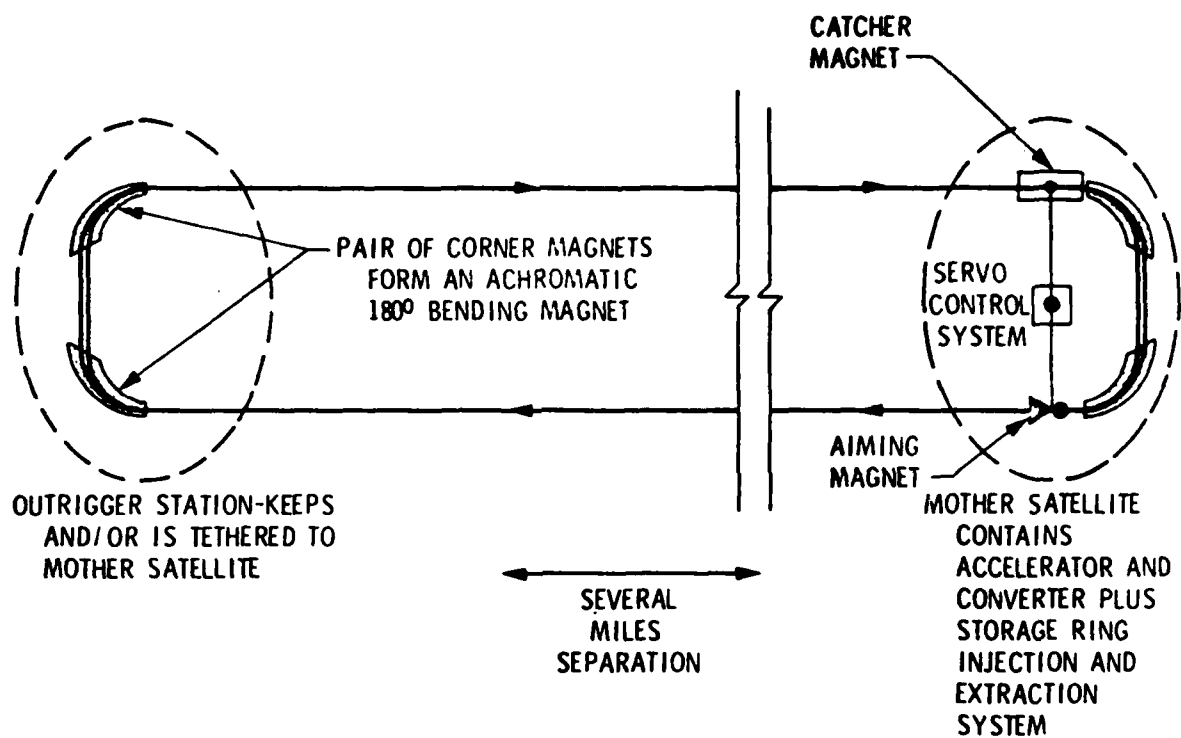


Fig. 7—"Skinny" race-track space storage ring

## THE SYNCHROBEAM GUN

High-power space lasers will employ secondary optics to attain small divergence beams. Such systems do not rely on the laser's monochromatic and coherent properties except to establish a small source size for the emitted optical radiation. Thus if we can achieve such a small source size (and with a reasonably forward-directed beam) by some other means, then we conceivably can approach the laser's low-divergence beam capability.

The Synchrobeam device was conceived for this purpose (by the author in 1972 in the course of ARPA investigations by Rand). Circulating electrons from a storage ring are passed into the solenoidal field of a 500 kG super-magnet. The fringing field of this magnet assists the e-beam in pinching down to a small diameter.\* The beam enters at a slight angle to the magnet's solenoidal field lines so that a component of the field transverse to the electron motive causes the electrons to spiral around the field lines. In so doing, they give off bremsstrahlung or synchrotron radiation in a forward cone.\*\* This optical radiation is collected by a large approximately paraboloidal mirror as shown in the attached sketch and focused on a ground (or space) receiver collector (Figure 8).

TABLE I presents parametric values for several different electron particle energies. Please note that beam injection angle (into the solenoidal field) is so adjusted in each case that the magnetic field component provides the right bending to produce the same  $\lambda_c = 1000\text{\AA}$  synchrotron spectrum for each electron energy case. The spectral band emitted encompasses the visible spectrum and except for a small amount of radiation at  $\lambda < 1000\text{\AA}$  and  $> 6000\text{\AA}$  uses conventional mirror surface materials of high reflectivities.

It is instructive to step through the 60 MeV case to see where certain tradeoffs lie in the system concept. As may be seen in TABLE I, each cycle or  $360^\circ$  rotation of the electrons produces  $7.5 \times 10^9$  watts of synchrotron radiation output for the  $2 \times 10^5$  ampere current assumed. Since one helical storage ring has nine beams of  $2.2 \times 10^4$  amperes, we can generate the required 0.62 gigawatt output beam by using several of these sub-beams at a time.

It should be noted that with, say, a 1200-meter focal length (see Fig. 8) as much as  $3.6 \times 10^{11}$  watts of output can be generated and handled by the optical system. The "source" becomes a spiralling electron beam 48 cycles long which is  $48 \times 2.5$  meters or 120 meters in length. A 10 : 1 ratio of focal length to extended source length is considered acceptable optical geometry. There is a potential problem since at this source length the "hole"

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\* Other methods might be employed to shrink the beam<sup>(6)</sup> including locally increased ion densities.

\*\* Note that this is a different method than customary wiggler transverse magnets used for producing synchrotron radiation. These transverse magnetic fields create a fan beam shape.<sup>(7,8,9)</sup> Helical wigglers have very recently been proposed<sup>(10,11)</sup> which produce effects similar to the Synchrobeam concept.

TABLE I

Synchro-beam calculations (500 kG solenoid)  
 (optical spectrum has  $\lambda_c = 1000 \text{ \AA}$ )

Electron Energy (MeV)	Beam Current* (Amp)	e V Loss/ Circuit/ Electron	Synchrotron Power/Cycle (W)	Half-Angle @ 3 dB Points (deg)	Field Component (kG)	Bend Radius (m)	Magnet Length/ Cycle (m)	Injection Angle (deg)
60	$2 \times 10^5$	30	$7.5 \times 10^9$	0.5	51.3	.0386	2.5	6
120	$4 \times 10^5$	60	$1.5 \times 10^{10}$	.25	12.8	.309	76	1.5
240	$8 \times 10^5$	120	$3 \times 10^{10}$	.125	3.2	2.47	2424	0.4
480	$1.6 \times 10^6$	240	$6 \times 10^{10}$	.063	0.8	19.76	77,600	0.09

\* Current = 1/10 Alfven limit



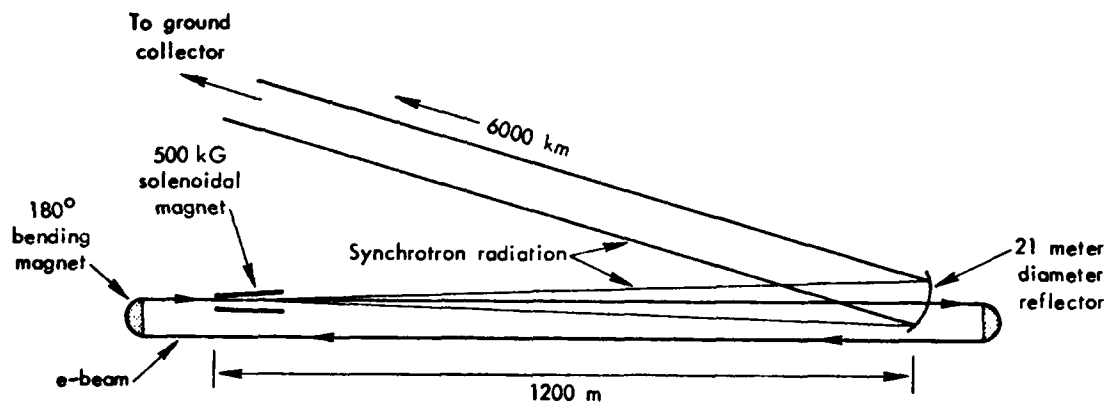


Fig. 8 — Synchrobeam optical power generator and link

in the 500 kG supermagnet must be  $> 2$  meters at the downstream end which is beyond the present state-of-the-art for such magnets.

However, at  $2/5$  of a synchrotron cycle (as needed to produce 3 GW) the hole size indicated is only a few cm and is considered feasible.

It should be noted that as electron particle energy is increased, the half-angle of the cone of emitted radiation decreases making it possible to employ smaller mirrors to aperture all of the light emitted. However, in the example selected here we are assuming transmitting the beam 6000 km (3750 miles) and we will find that even in the 60 MeV case the transmission mirror is diffraction limited (for the longer-wavelength half of the spectral band) so we cannot effectively use a smaller mirror anyway. Given a shorter range mission, the high electron-energy cases may be more advantageous--particularly since they are also more useful for ultra-high energy storage rings.

With reduced power, the source length is much less so we are not constrained to the 1200 meter focal length to achieve  $10 : 1$  over the source length. Assuming 21 meter (69 ft) diameter dish arbitrarily designing for  $\lambda = 4000\text{\AA}$  as the diffraction limiting criterion, we find that the effective divergence is  $.023\text{rad}$ . With the source spot (ring) diameter of 7.7 cm this permits a focal length of 560 meters for equivalent beam divergence. By ratioing source size, focal length, and transmission range we find a  $\frac{.0772}{560} \times 6000 \text{ km} = 827$  meter ground collector aperture requirement. There is the option to, say, double the space mirror size and halve the ground collector aperture. This tradeoff can only be made through judicious weighing of space and ground system operation and construction requirements and costs.

As an example of use of higher electron particle energy we consider the 480 MeV case. Here, by employing only  $1/600$ th of a cycle the source length is still 129 meters long. Synchrotron power is  $10^8$  watts (and inadequate for our gigawatt transmission requirement). Since only a small segment of a full  $360^\circ$  spiral of the electrons is used, the source becomes a long, almost straight, line in space--129 meters long and with a projected size (along the axis of synchrotron radiation) of 20.7 cm. Actually there is the choice of having two solenoidal magnets of opposite polarity so that the electrons spiral one way first and then spiral back (see Figure 9). With the double magnet configuration the source spot size is reduced to 10.4 cm. Only a 2.8 meter space dish is needed to collect the synchrotron radiation. However, with this size of mirror and a 6000 km range the ground collector would need to be 6 km in diameter due to diffraction limitations on the space collector.

This case has another problem in that care must be taken to assure that storage ring radii are large enough to preclude greater synchrotron radiation from the ring than via the transmission link. In fact, to achieve useful efficiency and avoid radiation damage problems ring radiation should be held to a few percent of transmitted power.

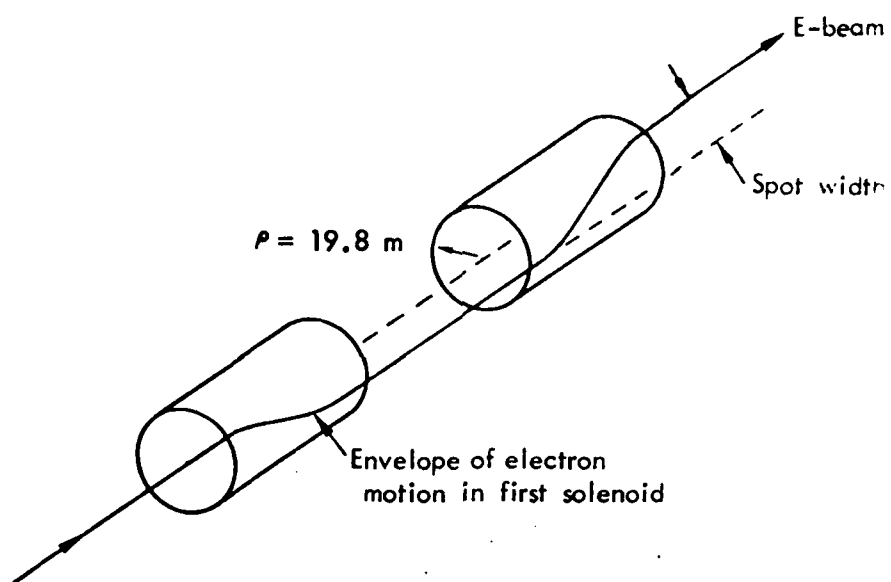


Fig. 9—Motion of electron beam at a small angle to two oppositely directed solenoidal fields

## GROUND ENERGY COLLECTION SYSTEM

The ground system assumed is in essence a solar-energy type of central electrical power generating station. The 830 meter aperture collector can take several forms. A large, fixed paraboloid (like a radio telescope) is one possibility. Alternatively we can consider a number of adjustable smaller mirrors with a common focus (similar to solar furnaces such as the one at Mont Louis in the Pyrenees). Although a heliotrope function is not needed, another similar but simpler requirement exists in tracking the satellite transmission. An angular variation of  $\pm 20^\circ$  is needed which might be accommodated through a "sloppy" focus design with some degradation of top cycle temperatures achieved.

Another collection alternative is to use arrays of collectors (and possibly power generating elements). The collector focal heat receptors can be connected together by heat pipes. Such a collector system compared to a large collection dish (or equivalent) is roughly analogous to a fresnel type field lens vs. a conventional one.

Collector arrays similar to the above were considered by the author for residential purposes.<sup>(12)</sup> It was found that overall system efficiencies competitive with central power stations could be predicted when accounting was made both for thermodynamic and collector efficiency. The high MHD power plant efficiencies projected for central power stations require high top temperatures. These in turn are collected at a penalty in percentage of total solar spectrum received compared to a lower top temperature that might be employed by recuperated Brayton cycle or Stirling cycle heat engines.

It is conceivable that an extrapolation of the array-type residential system could perform the central power collection and generation required for the concept outlined in this report. An array of 2400, 30m x 30m modules each generating 300 kw could be considered. The relatively small collecting dishes can be readily programmed to track the satellite transmission. An overall module generating efficiency of 23% is assumed (based on Reference (12)). Thus, 3 GW is received by the station and 0.7 GW is generated.

Use of ten equally-spaced satellites would permit more-or-less continuous transmission to each of the two ground receiver locations, each therefore generating  $\sim 0.7$  GW during peak solar collection periods. It should be noted that the Synchrobeam optical link will be unable to penetrate heavy cloud formations and will thus present availability problems in most regions of the world.

## CONCLUDING REMARKS

We have assumed a hypothetical low-altitude space solar energy collection and transmission system to illustrate potential use of space electron propagation and storage systems--and also to point up the prospects for such a low-altitude solar energy system itself.

The various concepts presented here can be considered separately. A low altitude solar collection system could be assumed that avoided storage requirements by having world-wide receivers, vehicle-to-vehicle energy relay, or simply sending back only 1/5 of the energy received. In place of the Synchro-beam link, we could consider an electron-pumped laser beam or an rf link. The latter might be energized by an auto-accelerator type of rf generator employing electron beams as the energy source.

Electron beam storage, energy conversion, and/or transmission systems as well as the Synchro-gun concept can be separately explored for other space solar collection schemes, such as geosynchronous, and for other space missions.

It should be cautioned that we are presenting concepts only--untested electron propagation phenomena coupled with hypothetical and unoptimized space system applications. Such if feasible, however, do point toward new alternatives for the future and ones which we should at least pursue to determine their potential utilization.

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